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Modelling study of the impact of thermal comfort criteria on housing energy use in Australia

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HIGHLIGHTS

- Impact of thermal comfort acceptability limit on housing energy use.
- Relaxing the acceptability limits has minor impact in regions without hot summer.
- Decrease from 90% to 70% in the acceptability can save energy by 40% in Darwin.
- Cooling energy can be minimized in tropical regions for lightweight houses.

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ABSTRACT

It is an increasing challenge for building designers in the 21st century to provide for thermal comfort at minimum energy cost by taking into consideration both the current and the future warming climate. Most previous studies have focused on thermal comfort in non-residential buildings under current climatic conditions. This study evaluates the impact of thermal comfort criteria by lowering the acceptability limits on space cooling energy requirements for Australian residential buildings, under both the current and projected future climates (with an assumed global warming of 2 °C) through building simulations using three different types of typical building constructions – lightweight, heavyweight, and a combination. The results show that under both current and future climates, relaxing thermal comfort criteria by lowering the acceptability limits from 90% to 70%, has a small or minor impact on space cooling energy consumption for the heavyweight and combination type construction in the subtropics (Brisbane), warm temperate (Sydney), temperate (Melbourne) and cool temperate (Hobart) climate regions. However, it has significant impact on space cooling energy consumption (saving more than 40%) in tropical regions (e.g. Darwin) and regions with a hot summer climate (e.g. Alice Springs and Mildura). For the lightweight type construction under the current climate, relaxing the acceptability limits will increase the energy star rating by 3.6 stars in Darwin, 0.5 star in Mildura, 0.3 star in Alice Springs and 0.2 star in Brisbane. Under the projected future climate, relaxing the acceptability limits to 70% will increase the energy star rating by 1.6 stars in Darwin, 1.2 stars in Brisbane, 0.7 star in Alice Springs and 0.3 star in Mildura. It was also found that for all the climates, relaxing the acceptability limits from 90% to 80% has greater impact than that from 80% to 70%. By relaxing the acceptability limits, the space cooling energy consumption can be minimized in tropical and subtropical regions for high set lightweight houses.

1. Introduction

Globally, buildings consume around 70% of end-use energy for space heating, cooling, ventilation and artificial lighting [1]. As demonstrated in the literature [2], high energy consumption of air-conditioning is not necessarily required to achieve thermal comfort in many cases. Large amounts of energy can be saved by allowing air-conditioning systems to operate under a wider range of indoor temperature fluctuations. In recent years, thermal comfort in buildings has attracted the attention of many researchers worldwide, partly due to the increased public awareness of climate change [1]. Given the increasing costs of energy and the awareness of climate change, it is increasingly necessary to optimize thermal comfort settings to consider both energy use and climate change together.

In ASHRAE 55 [3], thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Apart from cultural influences, thermal comfort depends upon environmental and personal factors. It is

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complicated to predict the range of temperatures for this comfort condition. Thermal comfort has been discussed since 1930s. Climate chamber tests and field studies are two approaches used in the field of thermal comfort. Steady-state models were developed from climate chamber tests, which were based on heat exchange processes of the body, such as the widely used Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) model [4]. Most of the steady-state models were developed prior to the field studies.

Field studies conducted in real buildings led to adaptive thermal comfort models, which were based on the adaptive principle that occupants are active and not passive (the PMV method) relating to their thermal environment, i.e., “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [5]. To do that, occupants may change their clothing, posture, activity, etc. or change their surrounding environment using windows, blinds, fans and in certain conditions mechanical space heating or cooling. People may also move around to find a room with improved conditions. Under the hypothesis of adaptive thermal comfort where people gradually lessen the human response to repeated environmental stimulation through both behavioural and physiological as well as psychological adaptation, and the fact that past thermal history will modify the occupant’s thermal expectations and preferences, people in warm climates will prefer higher indoor temperatures than those living in cold climates [6]. A number of studies show that the range of comfort temperatures in naturally ventilated buildings or mixed-mode buildings is much wider than what PMV-PPD predict [7–10].

The adaptive method was developed from field studies in mainly naturally ventilated office buildings [6,11–16] by relating indoor operative temperatures (acceptable ranges) to prevailing outdoor temperatures. The acceptable range is the comfort temperature band within which the great majority of people, described by the percentage of acceptability, are adequately comfortable. This acceptable temperature range is wider than ‘ideal’ conditions and would encompass feeling such as ‘slightly cool’, ‘slightly warm’ and ‘neutral’. Thermal comfort is subjective and personal, and there may be no single condition that is comfortable for all the occupants at any given time. Furthermore, the heating and cooling capacities required would be prohibitive if the acceptable temperature range has to be met for 100% of the occupancy time, even during extreme weather conditions [17].

Thermal comfort studies in buildings have been recently reviewed [1,18–21]. These studies discussed the research on steady-state and adaptive thermal comfort, as well as thermal comfort standards for naturally ventilated, air-conditioned and mixed buildings. Field studies in educational, office, residential and other building types were also examined. A number of other studies [22–28], have focused on the investigation of thermal comfort and energy efficiency. As mentioned in [20], in general, these studies of the energy use implications of thermal comfort in built environment can be grouped into two areas: case studies (HVAC, heated or cooled buildings) and implications for thermal comfort standards.

Most of the case studies for heating and cooling of buildings focused on increasing the summer set point temperature (SST) or setting a variable indoor set point temperatures for different times of the day and different outdoor conditions. Two major types of control strategies were proposed. The first type involved diverse thermostat techniques through changing the setback period, set point temperature, and setback temperature [29]. To have a better understanding the trade-off between thermal comfort and energy consumption, attempts have also been made [30,31] to correlate cooling energy consumption with corresponding thermostat operational mode. The second type of control strategy covered deals with the dynamic control of the set point temperature based on adaptive thermal comfort models [32,33]. Case studies summarized in [20] show that substantial energy can be saved for both office and residential buildings, ranging from 6% reduction in HVAC electricity usage in Australian office buildings (by increasing 1 °C in the SST) [34] up to a 33.6% reduction in total energy cost in hot desert region in Riyadh [35].

To offer a uniform method for the building industry and the general public, many studies have been undertaken on the implications of thermal comfort standards since early 2000s, including the works by de Dear and Brager [10] for global general buildings; Van der Linder et al. [36] for office buildings in Netherlands; Ogbonna and Harris [37] for classroom, studio and residential buildings in Nigeria; Nicol and Humphreys [38] for global general buildings; Nicol and Humphreys [13] for office building in Europe; Roaf et al. [39] for global general buildings; Yao, Liu and Li [40] for university classroom buildings in China; Indraganti [41] for residential buildings in India; Panao, Camelo and Goncalves [42] for residential and “small service” buildings in Portugal; Cândido et al. [43] for non-domestic buildings in Brazil; Yun, Kong and Kim [44] for office buildings in South Korea; Liang, Lin and Hwang [45] for school buildings in Taiwan; and Li et al. [46] for two types of buildings (heated/cooled or free-running mode) in China.

Nowadays the international standards commonly used to evaluate the thermal environments are ISO 7730-2005 [47], ASHRAE 55-2013 [3] and EN 15251-2007 [48]. The Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) method, which was based on Fanger’s theory [4], is the basis of ISO 7730-2005 and the Graphic and Analytical Comfort Zone methods in the ASHRAE 55-2013 standards. Both EN 15251-2007 and ASHRAE 55-2013 standards adopted the adaptive thermal comfort method for the evaluation of the indoor environment of naturally ventilated buildings. The ISO 7730-2005 standard does not incorporate the adaptive thermal comfort method, but specifies the thermal indoor environment to be within 70% of the acceptability limit for naturally ventilated buildings [17]. For naturally conditioned spaces, ASHRAE 55-2013 specifies the acceptability limit to be 80%. To meet high occupant expectations of thermal environments, the acceptability limit of 90% is specified in ASHRAE55-2013. The PPD is the complement of the thermal acceptability. For the three acceptability limits mentioned above the PPD are 30%, 20% and 10% respectively.

Most previous studies have been concentrated on non-residential buildings. Compared to non-residential buildings, occupants of residential houses generally have greater opportunities (subject to the capabilities of the building and its systems) to decide and create thermal comfort conditions themselves. Given the large overall energy consumption from the residential sector, increasing energy prices, and changing climate, there is an increasing interest in the study of impact of different thermal comfort models (standards) on residential energy consumption. For instance, Attia and Carlucci [49] conducted a simulation study to compare the impact of four models (Fanger’s model in ISO 7730, the ASHRAE55 adaptive comfort model, the EN15251 adaptive model and Givoni’s model) on energy consumption and thermal performance for a zero energy multi-residential building in hot climates. This study shows, that to meet the thermal comfort criteria according to ISO 7730 in comparison to EN1521, ASHRAE 55 or Givoni’s model, the percentage of energy consumption difference varied up to 16%, 21% and 24.7%, respectively. Kim et al. [50] carried out a field study of air conditioning and thermal comfort in residential buildings in Sydney and Wollongong, Australia. They found that the comfort zone widths for 80% acceptability were 9 K in residential settings, which is 2 K wider than that expected by the adaptive model. Shiel et al. [51] presented a simulation case study to estimate the space heating and cooling energy of a one-bedroom residential building in a warm temperate climate (Adelaide, South Australia) with global warming using alternative Standard Effective Temperature (SET^*) comfort approaches. For the SET^* comfort approaches, the acceptability limits of 90% and 80% were also evaluated. The results from their study showed that the SET^*80% approach with air movement, changed clothing and occupant acclimatization can save over 95% of the Nationwide House Energy Rating Scheme (NatHERS) residential heating and cooling energy. Shiel et al. [51] suggested that more research is needed for the inclusion in NatHERS.

A few studies [52–54] have investigated the potential energy saving of non-residential buildings through adaptive thermal comfort approaches under climate change conditions. Case studies made in [52] for school and office buildings in United Kingdom indicate that high mass buildings are capable of providing a high quality of indoor thermal comfort when all the principles of low-energy and sustainable design are applied considering current and future climates. Touhy et al. [53] investigated the impact of two adaptive thermal comfort approaches on comfort and energy demand of a London office building. Variables such as future climate, future building upgrades, internal heat gains, setback temperatures and ventilation were also explored. The study suggests that for a typical office building under 2005 and predicted 2080 London climates, the building could achieve close to zero energy demand for space heating and cooling by a combination of strategies. Wan et al. [54] developed regression models to predict energy consumption of office building air conditioning for five typical climate regions in China under different climate change scenarios. An increasing trend of cooling load and a decreasing of heating load due to climate change in future years were predicted. As mentioned in [20], more work is required to analyse how, and to what extent future global warming impacts the applicability of adaptive thermal comfort models already developed and used in different regions worldwide.

Nicol [55] collected information from dwellings in a range of climates and buildings and found a very wide range of indoor temperatures in dwellings, which may be naturally ventilated or mechanically heated or cooled. The evidence from Nicol [55] suggests that the adaptive behaviours of building occupants occur when buildings are mechanically heated or cooled as well as when they are naturally ventilated and free-running. It is debatable how realistically these ranges can be acceptable in residential buildings and how different the ranges achieved by adaptive measures in houses can be [17].

There are a variety of climates across Australia, from the tropical north to the temperate south-east (such as much of Victoria and Tasmania). Currently, Australian Nationwide House Energy Rating Scheme (NatHERS) adopts a variation of the ASHRAE 55-2013 adaptive thermal comfort method with a criterion of 90% acceptability limit [56]. It has been debated that such a high acceptability requirement may be too strict for residential buildings, especially for tropical regions. It is arguable that a criterion of 80% acceptability proposed in ASHRAE 55-2013, or even 70% in ISO 7730-2005 may be adequate for Australian residential building applications.

Generally, for heating and cooling, less energy is required to maintain a broader indoor air temperature range than for a narrower range. However, to date there has been little critical analysis on the impact of the indoor temperature range (i.e., acceptability limits) on housing heating and cooling energy requirements for different constructions in different climate regions under current and future climates. This study intends to fill in this research gap by investigating the impact of acceptability limits of indoor temperature on residential building energy performance under current and future climates through building simulation using AccuRate [57]. The current study provides the understanding for potentially relaxing the thermal comfort acceptability limits currently used in the house energy rating tools by the Australian building industry. A range of Australian climate zones are considered for three typical house constructions. Specifically, the study presented in this paper comprises of the following components:

(a) Based on the adaptive model and commonly used standards, three types of thermal comfort criteria were proposed and implemented into the AccuRate software for case studies (Sections 2.1 and 2.3);
(b) With global warming of 2 °C, the future weather files were constructed for the seven main Australian climate regions (Section 2.2);
(c) Evaluation of the impact of the thermal comfort criteria on two types of typical houses (heavyweight and combined) in the seven regions (cities) was conducted under the current climate (Section 3.1) and future climate (Section 3.2);
(d) Evaluation of the impact of the thermal comfort criteria on lightweight housing typical in tropical and sub-tropical regions was presented for current and future climate (Section 3.3);
(e) Findings from (c) and (d) were summarized (Section 4), demonstrating that the impacts of the thermal comfort acceptability limits on space cooling energy are substantial in regions with hot summers, especially for high set lightweight houses.

2. Methodology

2.1. Simulation of energy performance of residential buildings

In ASHRAE 55-2013, the comfort standard for naturally conditioned spaces has a mean comfort zone band of 7 K for 80% acceptability limits, and 5 K for 90% acceptability limits (note that the 90% acceptability limits are included for situations when a higher standard of thermal comfort is desired). The study herein investigates the impact of different comfort zone bands (i.e., acceptability limits) on housing energy performance using building simulations. Building simulations were carried out with a modified version of AccuRate [57], which allows a variety of thermostat settings [58]. AccuRate was developed to simulate the energy requirements for space heating and cooling by coupling a frequency response building thermal model [59] and a multizone airflow model [60]. Taking into account the building fabric and local climate, AccuRate automatically switches the building operation between mechanical air conditioning and natural ventilation if natural ventilation satisfies the occupant thermal comfort. It calculates a year hourly energy requirement for space heating and cooling (H/C). Based on the annual total H/C energy requirement, a star rating between 0 and 10 stars is assigned to the residential building for a specific climate zone using the star bands defined by NatHERS) [61]. As specified by NatHERS, 0 star means the building shell does nothing to protect the occupants against outdoor environment, and occupants of a 10 stars house are unlikely to need any artificial heating or cooling. The more stars, the more energy efficient the house is. The AccuRate engine was tested satisfactorily against BESTTEST [62].

The thermostat settings used in AccuRate for house energy rating are based on the Protocol for House Energy Rating Software published by Australian Building Codes Board [63] and described as follows.

For the heating thermostat setting, 20 °C is used for living spaces (kitchen and other spaces typically used during the waking hours). 15 °C is used from 24:00 to 7:00 and 18 °C from 7:00 to 9:00 and 16:00 to 24:00 for sleeping spaces [57].

For the cooling thermostat setting, a combination of the adaptive thermal comfort method [3] and the new effective temperature (ET*) by Aynsley and Szokolay [64] is used, which takes into account air temperature, air movement speed, mean radiant temperature and humidity [56,57].

In AccuRate, the neutral temperature and the cooling effect of air movement are given by:

$$T_n = 17.8 + 0.31 \times T_{om} \tag{1}$$

$$\Delta T = 6 \times (U - 0.2) - 1.6 \times (U - 0.2)^2 \tag{2}$$

where T_n (°C) is the neutral temperature, i.e. the temperature at which occupants feel neither too cold nor too warm; T_{om} (°C) is the mean monthly outdoor temperature. ΔT (°C) represents the cooling effect of air movement and U (m/s) is the air movement speed and is limited to 1.5 m/s [57].

In AccuRate, the cooling thermostat is set equal to the neutral temperature defined in Eq. (1) for the corresponding climate zone, up to a limit of 28.5 °C, above which both are taken to be 28.5 °C. The upper and lower limits of the comfort zone at 50% relative humidity is taken to be $T_n \pm T_{al}$ (T_{al} is the upper/lower temperature bandwidth of the comfort zone, 2.5 °C was used in the current version of AccuRate, corresponding to the 90% acceptability limit in ASHRAE 55-2013) .

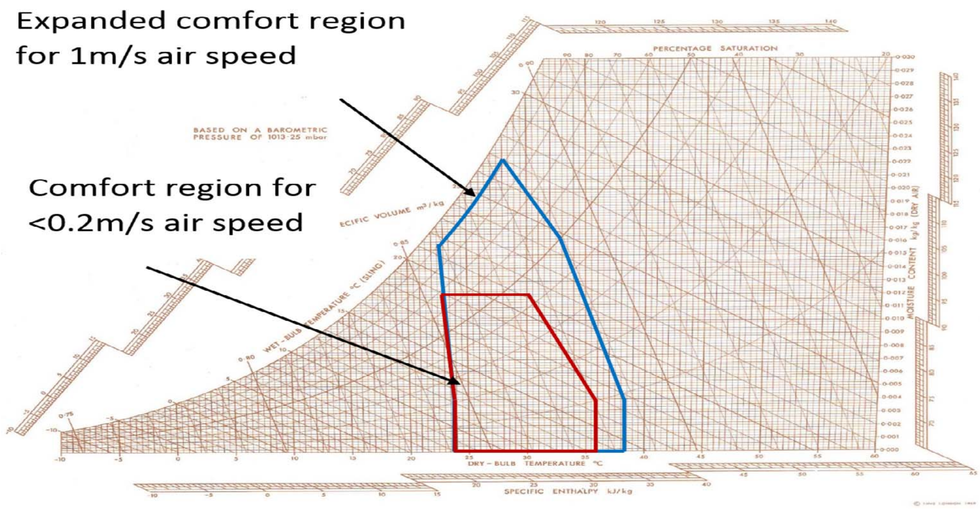

Fig. 1. Comfort region in Darwin for air movement below 0.2 m/s (smaller region), and expanded comfort region for air movement of 1 m/s.

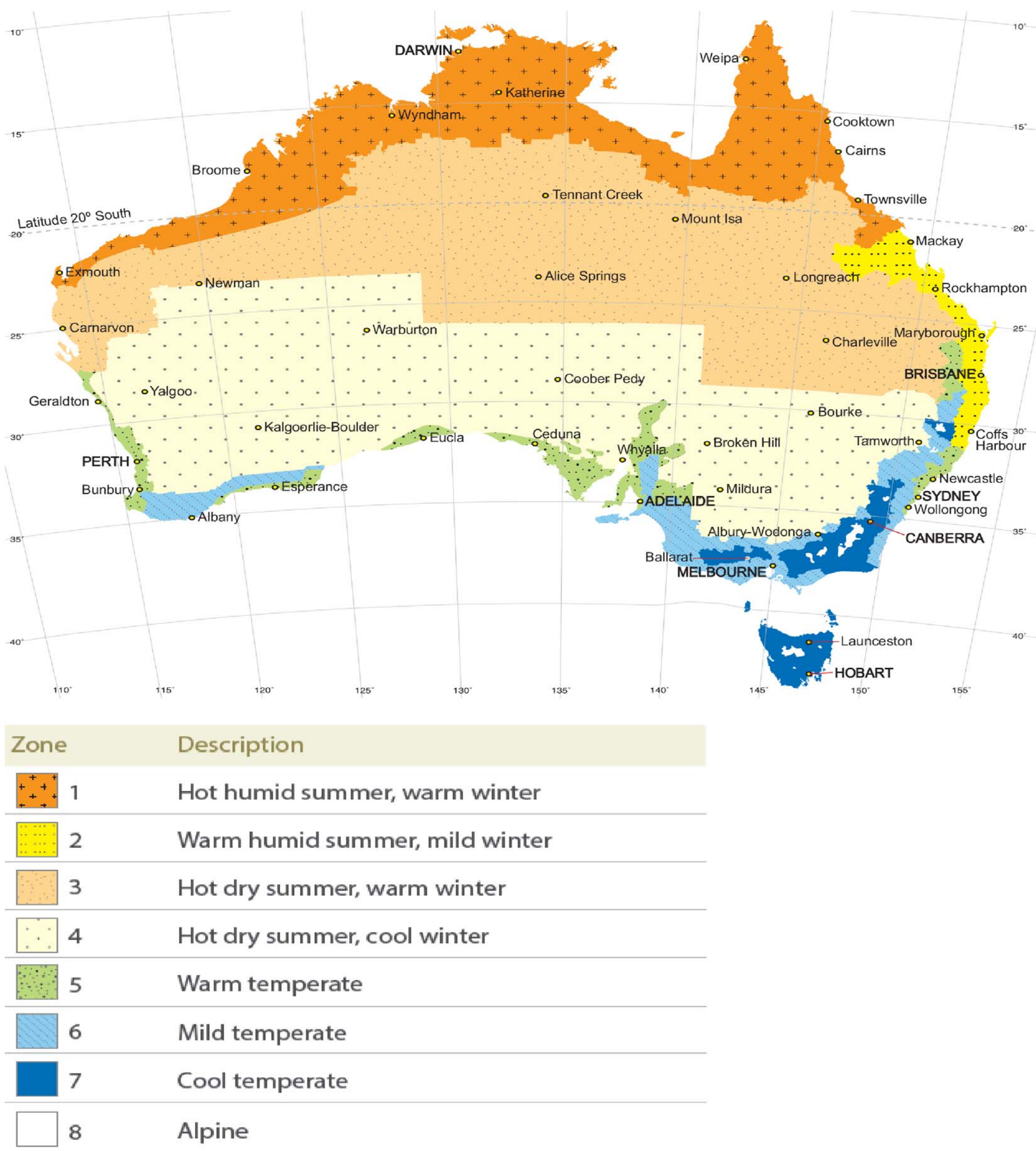

Fig. 2. Australian climate zones (adapted from [63]).

When the impact of air movement is considered, the comfort zones will be extended. Fig. 1 shows an example of how the comfort zones can be established for Darwin on a psychrometric chart. The smaller comfort zone is for indoor air speed below 0.2 m/s, while the larger comfort zone is for 1.0 m/s indoor air movement. The lower horizontal boundaries of the low limit of humidity ratio have been placed at 0 g/kg in AccuRate considering that cooling should not be invoked only because the air is too dry (i.e. below 4 g/kg), though normally the lower boundary would be placed at 4 g/kg humidity ratio in either case. This is consistent with the graphic comfort zone method in ASHRAE standard 55-2013 [3] which suggests no lower humidity limit.

For the upper boundary, it has been set at 12 g/kg humidity ratio for air movement below 0.2 m/s. For air movement of 1.0 m/s, this upper limit is raised to 90% relative humidity (RH) to reflect the benefit of natural ventilation. For 4 g/kg humidity ratio or above, the left boundary is the ET* line corresponding to the lower temperature limit of 24 °C, which is 2.5 °C below the Darwin neutral temperature of 26.5 °C for cooling purposes. For humidity ratio less than 4 g/kg, both the left and right-hand boundaries are vertical lines at the temperatures from where the ET* lines cross the 4 g/kg line.

For the right boundary, without air movement, the boundary is the ET* line that passes through the 50% line at the upper temperature limit of 29 °C (the neutral temperature of 26.5 °C plus 2.5 °C). The slope of the ET* is negative due to the acceptable dry-bulb temperature decreasing with the humidity increasing. With air movement, the right boundary is the ET* line that passes through the 50% line at a temperature of $T_n + 2.5 + \Delta T$. For the air movement of 1.0 m/s, Eq. (2) gives ΔT of 3.8 °C, as shown in Fig. 1 the extended upper temperature limit for Darwin at 50% RH is now 32.8 °C (26.5 + 2.5 + 3.8).

In AccuRate, at each hour the zone temperature and humidity with natural ventilation (no cooling) is first calculated. The air speed at each opening is calculated based on the air flow rate at the opening, and the opening area. The mean air speed of all the openings of the zone is estimated to be the air speed in that zone. The air temperature and humidity in the zone with this air speed are then compared to the comfort zone, which is extended according to the air speed. The simulation proceeds to the next hour if the zone condition is within the comfort zone. Otherwise, natural ventilation is switched off (i.e., occupant-controlled openings, such as windows and doors, are closed) and the cooling energy is calculated based on maintaining the zone temperature at the cooling thermostat setting.

2.2. Australian climate zones and future climate

Using different adaptive thermal comfort criteria for building designs can have different impacts in different climates, especially in hot climate regions [2]. The current study focuses on Australia. However, the general findings should be applicable to similar climates worldwide. As defined by the National Construction Code (NCC), there are eight NCC climate zones across Australia (Fig. 2). The main characteristics of the eight NCC climate zones are summarized in Table 1. Within each NCC climate zone, there are many regional sub-zones, which are determined by local geographic features including wind patterns and height above sea level. 69 of these sub-zones are identified by NatHERS, which cover the whole Australia. They can be called up by postcode defined by NatHERS. AccuRate contains 69 TMY (Typical Meteorological Year) weather files with hourly data for a period of one year for the corresponding climate sub-zones. The main weather parameters are dry-bulb temperature, absolute humidity, atmospheric pressure, wind speed and direction, cloud cover, direct solar irradiance and diffuse solar irradiance.

The TMY files were composed using weather data from the 1970s to 2000s. They are assumed to be the reference climates for building energy simulation for the current climates. With global warming projections by models for the assessment of greenhouse gas induced climate change or a global warming scenario (e.g., 2 °C), climate changes in Australia can be simulated using Global Circulation Models (GCM) [65]. In this study, changes in the monthly-mean local ambient temperature, relative humidity and solar radiation since 1990 were projected using the GCM of CSIRO MK3.5 [66] in relation to the global warming temperature. Then the future hourly weather data are constructed using 'morphing' approach [67] as described in Eqs. (3)–(5).

$$T = T_0 + \Delta T_m \tag{3}$$

$$RH = RH_0 + \Delta RH_m \tag{4}$$

$$I = (1 + \alpha_m) I_0 \tag{5}$$

where T, RH and I are the projected future hourly dry-bulb ambient air temperature (°C), relative humidity (%) and solar radiation intensity (W/m^2) respectively; Δ represents changes in corresponding weather parameters; α_m represents the percentage change of solar radiation (%); subscript *0* represents the reference climate and subscript *m* represents monthly-mean.

In Australia, the average temperature has increased by 0.9 °C since 1950 with significant regional variations [65]. The Paris Agreement of climate change set out a global action plan to keep global temperature increases by the end of the century to a manageable 2 °C (http://en.wikipedia.org/wiki/Paris_Agreement). In this study, the global warming temperature of 2 °C is used for Australian future climate projections.

2.3. Acceptability limits and representative cities used in case study

Three different levels of acceptability (category A for 90%, B for 80% and C for 70%) are introduced in the standards ISO 7730 and ASHRAE Standard 55. To evaluate the impact of acceptability limits on residential building thermal performance, these three levels of acceptability were used for simulation in this study. The upper/lower temperature bandwidth (T_{al}) of the comfort zone is shown in Table 2.

Considering that there are very few residential buildings in NCC climate zone 8 (Alpine), this case study focuses on the remaining seven NCC climate zones (zones 1–7), in which a main city is chosen to be representative of the corresponding NCC climate zone (Fig. 2). The cooling thermostat settings for each city are based on the Protocol for House Energy Rating Software published by Australian Building Codes Board [63], which are calculated by Eq. (1) and given in Table 3. As listed in Table 3, the greatest difference of the cooling thermostat settings among these cities are 3.5 °C (i.e., 26.5 °C in Darwin and 23 °C in Hobart).

2.4. Descriptions of the residential buildings

In Australia, around 70% of the dwellings are detached houses [69]. To illustrate the impact of acceptability limits on energy requirement for air conditioning, three typical detached houses of different sizes and constructions (lightweight, heavyweight and combination) are used for simulation in this study. Houses 1 and 2 are two of the eight sample houses previously used for energy rating software accreditation by NatHERS. Both houses have the common concrete slab-on-ground floor construction. House 1 is a single-storey house with colorbond external wall (steel cladding on 90 mm stud). House 2 is a two-storey house with double brick cavity external wall.

House 1 (Fig. 3) has four bedrooms, a kitchen/family area, a dining/lounge area, a laundry, a separated bathroom and toilet. It has a gross floor area of 160 m^2 with 140.8 m^2 air-conditioned. House 2 (Fig. 4) has four bedrooms, a kitchen/family area, a dining/living area, a rumpus, a study, a TV room, a laundry, a separated bathroom, a toilet and a double garage, with a gross floor area of 267.9 m^2 (195.4 m^2 air-conditioned). In this study, the floor plans for both houses were maintained, while various changes of wall insulation, ceiling insulation, window types, infiltration controls etc were used to achieve energy star ratings (under current climate and acceptability of 90%) of around 3

Table 1
Main characteristics of Australian climate zones (adapted from [68]).

Climate zone	Main characteristics
Zone 1- Hot humid summer, warm winter	• High humidity with a degree of 'dry season' • Temperature: moderate to high for year round, low to moderate for seasonal variation, and minimal diurnal (day-night) range
Zone 2- Warm humid summer, mild winter	• High humidity with a definite 'dry season' • Temperature: hot to very hot summers with mild winters, distinct summer/winter seasons, and low to moderate diurnal (day-night) range, which can vary significantly between inland and coastal
Zone 3- Hot dry summer, warm winter	• Distinct wet and dry seasons, low rainfall and low to moderate humidity • Temperature: hot to very hot summers common, no extreme cold but can be cool in winter, and significant day-night range
Zone 4- Hot dry summer, cool winter	• Distinct seasons with low humidity year round, and low rainfall • Temperature: very hot summers common with hot dry winds, cool winters with cool dry winters, and high day-night range
Zone 5- Warm temperate	• Low to moderate humidity in summers and low humidity in winters • Temperature: hot to very hot summers, mild winters, and high day-night range inland and moderate day-night range near coastal • Four distinct seasons: summer and winter can exceed comfort range, and spring and autumn are ideal for human comfort.
Zone 6- Mild temperate	• Moderate humidity in summers and low humidity in winters • Temperature: hot to very hot summers, mild to cool winters, and high day-night range inland and low day-night range near coastal • Four distinct seasons: summer and winter cab exceed comfort range, and spring and autumn are ideal for human comfort.
Zone 7- Cool temperate	• Low humidity and winters with majority of rainfall • Temperature: hot dry summers, cold to very cold winters, and high day-night range • Four distinct seasons: summer and winter exceed human comfort range, highly variable spring and autumn conditions.
Zone 8- Alpine	• Low humidity, dry summers and winters with majority of rainfall and some snow • Temperature: warm to hot summers, cold to very cold winters, and high day-night range • Four distinct seasons: summer and winter exceed human comfort range, highly variable spring and autumn conditions

Table 2
The comfort zone upper/lower temperature bandwidth for each acceptability limit.

Acceptability (%)	Upper/lower temperature bandwidth (K)	Source
90	2.5	ASHRAE Standard 55-2013
80	3.5	ASHRAE Standard 55-2013
70	4.0	European Standard 15251

Table 3
Cooling thermostat settings for the representative cities.

NCC climate zone	Representative city	Climate sub-zones defined in NatHERS	Thermostat setting temperature (°C)
Zone 1	Darwin	1	26.5
Zone 2	Brisbane	10	25.5
Zone 3	Alice Springs	6	26.5
Zone 4	Mildura	27	25.0
Zone 5	Sydney	17	25.5
Zone 6	Melbourne	21	24.0
Zone 7	Hobart	26	23.0

stars for House 1 and around 6 stars for House 2 in the seven cities (Table 3). House 1 with 3 stars are selected to represent housing stock built between 1990–2004, and House 2 with 6 stars represent new housing stock built since June 2011 that satisfy current NCC energy efficiency standard [70]. These houses (House 1- combination construction, House 2- heavyweight) are evaluated for all the seven climate zones.

House 3 is a high set (2.32 m fully raised off the ground) single-storey house with weatherboard external wall and timber floor, which is a typical passive house designed for tropical and sub-tropical regions. This high set lightweight house is evaluated only in tropical, sub-tropical and hot climate regions (i.e., zones 1–4). House 3 (Fig. 5) has three bedrooms, a kitchen/living/hall, a laundry, a separated bathroom and toilet, with a gross floor area of 90.7 m^2 (70.8 m^2 air-conditioned).

Thermal mass is effective in regions that have large diurnal (day-night) temperature ranges, for instance, in NCC climate zones 3 and 4 (see Table 1). For climates with year-round hot or cold weather, thermal mass effect can actually be detrimental as all surfaces of the mass tends towards the average daily temperature, which may be above or below the comfortable range. For example, in tropical regions buildings with lightweight construction may be more comfortable during night by cooling down much quicker than heavy weight constructions.

3. Results: case study simulations

3.1. Simulation results for houses 1 and 2 in the seven climate regions under current climate

In terms of the space heating and cooling energy requirement, the eight climate zones defined by NCC (Table 1) can be grouped into three typical regions: heating dominated, cooling dominated and heating/cooling balanced. As mentioned above, there are very few residential buildings in NCC climate zone 8, this study is thus focused on the remaining seven NCC climate zones. The results for House 1 with around 3 stars and House 2 with around 6 stars under current climate (TMY) are presented in Fig. 6.

In the three typical regions (Darwin-cooling dominated, Hobart-heating dominated, and Brisbane-heating/cooling balanced), the results show that for both houses there are no energy requirements for space cooling in Hobart and space heating in Darwin. For House 2 the decrease from 90% to 70% in the acceptability limits has no impact on the cooling loads in Brisbane and Hobart, and reduces 3.1% of the cooling load in Darwin (0.2 star increased from 6.1 to 6.3 stars). For House 1 there is a minor impact on the space cooling loads in Brisbane and Hobart due to the decrease in the acceptability limits from 90% to 70%. However, in Darwin it reduces 13.7% of the cooling load and increases 1 star in the energy rating from 3.1 to 4.1 stars. It also shows that for both houses in Darwin the decrease from 90% to 80% in the acceptability limits has greater impact on the cooling load than that from 80% to 70%. Specifically, for House 1, the reduction from 90% to 80% increases 0.7 star (i.e. from 3.1 to 3.8 stars) and the reduction from 80% to 70% increases only 0.3 star (i.e. from 3.8 to 4.1 stars).

The results also show that the energy requirement for space heating in Alice Springs (hot dry summer with warm winter) is less than in Mildura (hot dry summer with cool winter) and the impact of the acceptability limits on the space cooling load in Alice Springs is relatively greater than that in Mildura. The cooling loads for Houses 1 and 2 are reduced by 48.4% and 41.9% respectively due to the decrease in the

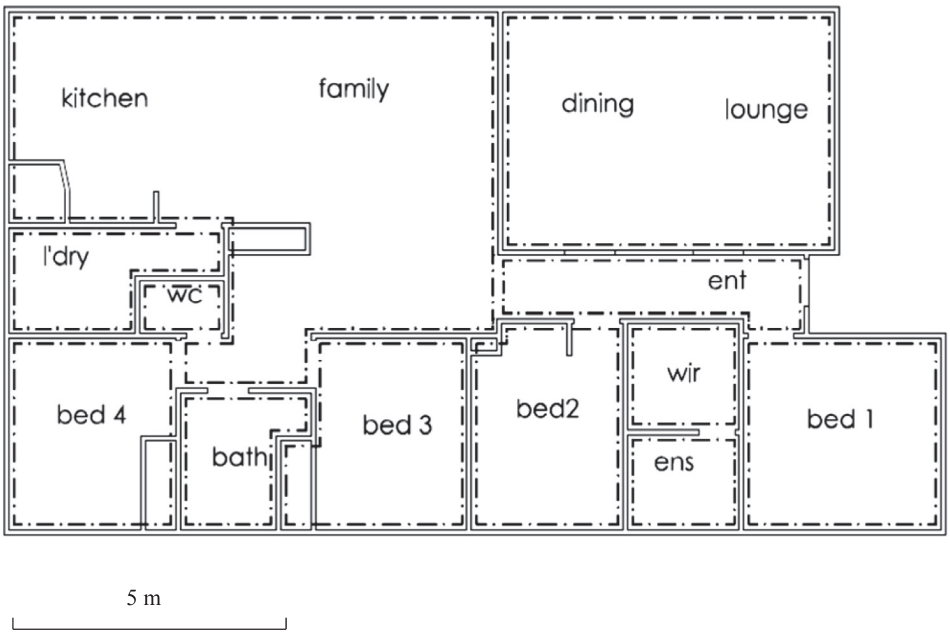

Fig. 3. The floor plan of House 1.

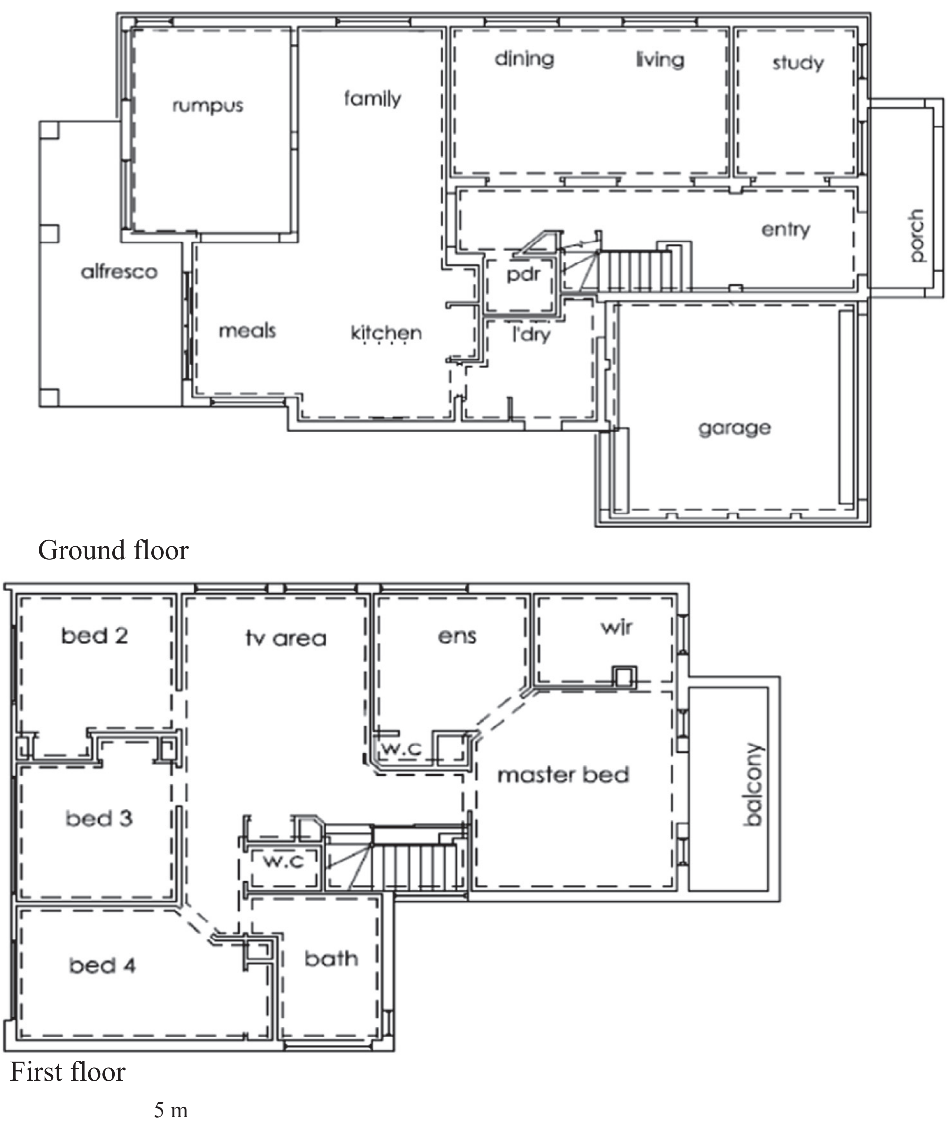

Fig. 4. The floor plan of House 2.

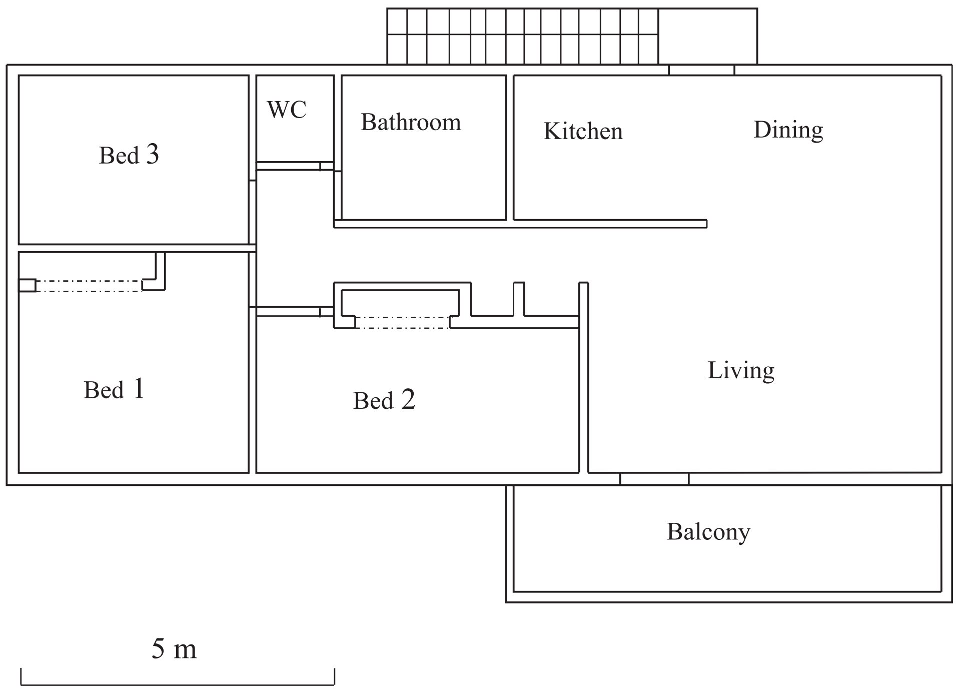

Fig. 5. The floor plan of House 3.

acceptability limits in Alice Springs. The reductions are 45.8% and 35.0% for Houses 1 and 2 in Mildura respectively. For House 1 it increases 0.6 star (from 3 to 3.6 stars) in Alice Springs and 0.1 star (from 2.9 to 3 stars) in Mildura due to the decrease from 90% to 70% in the acceptability limits. For House 2 the increase is 0.4 star (from 5.9 to 6.3 stars) in Alice Springs and 0.2 star (from 5.9 to 6.1 stars) in Mildura. The impact of the acceptability limits on star rating is higher in Alice Spring due to the fact that the cooling load is relatively a larger component of the total heating and cooling loads in comparison with that in Mildura. Again, it was found that for both houses in the two cities the decrease from 90% to 80% in the acceptability limits has a greater impact on the cooling loads than that from 80% to 70%.

The impact of the acceptability limits on space cooling loads is limited in both Sydney and Melbourne. In terms of house energy star rating, their impact can be ignored (i.e., star rating for both houses in the two cities has no change with the decrease from 90% to 70% in the acceptability limits) due to the fact that cooling loads are significantly small in comparison with heating loads.

As mentioned previously, there has been little critical analysis on the impact of the acceptability limits on space cooling loads, it is hard to find data for comparison. From the study for the regions with hot summer by Hoyt et al. [2], in which the software EnergyPlus was used to investigate the energy implications of large range of thermostat setpoints, Arens et al. [71] concluded that the difference of space heating/cooling energy use of residential buildings will be around 20–30% between the adjacent classes (A, B, C). The results from present study for regions with hot summer (Darwin, Alice Springs and Mildura) are within the range of Arens et al.

In general in the seven NCC climate regions under current climate, for space cooling loads, the acceptability limits have greater impact on the medium weight colourbond slab-on-ground construction (House 1) than on the heavy double brick cavity construction (House 2), and the decrease from 90% to 80% in the acceptability limits has a greater reduction than the decrease from 80% to 70%. The acceptability limits have the most impact on the house energy star rating in tropical regions (Darwin), medium impact on hot-summer regions (Alice Springs and Mildura), and minor or no impacts on energy star rating in Brisbane, Sydney, Melbourne and Hobart.

3.2. Simulation results for houses 1 and 2 under future climate in the seven climate regions

With an assumed global warming temperature of 2 °C, the predicted results for Houses 1 and 2 in the seven climate regions are shown in Fig. 7. With global warming up to 2 °C, for both houses 1 and 2, there are almost no energy requirements for space cooling in Hobart. As expected, global warming increases space cooling loads (except for Hobart) and reduces heating loads (except Darwin which has no heating energy requirement). The impact of the global warming on House 1 and House 2 energy star ratings are shown in Table 4. With regard to house energy star rating for both houses, Darwin lost the most stars (3 stars decrease from 3 stars to 0 star for House 1 and from 6 stars to 3 stars for House 2) due to significant increase in the cooling loads (see Figs. 6 and 7), while Melbourne gets the most benefit (1.4 stars increase from 3 stars to 4.4 stars for House 1 and from 6 stars to 7.4 stars for House 2) due to the reduction in the heating loads larger than the increase in the cooling loads (see Figs. 6 and 7).

Under global warming of 2 °C, the decrease from 90% to 70% in the acceptability limits has minor or no impacts on the cooling loads in Brisbane, Sydney and Hobart (see Fig. 7), while the cooling loads in Melbourne are reduced by 9.5 MJ/m^2.annum for House 1 and 2.7 MJ/m^2.annum for House 2. In terms of house energy star rating, the decrease in the acceptability limits has no impact on House 1 in Sydney, and House 2 in Sydney, Hobart, Brisbane and Melbourne (Table 4). Star rating is increased 0.1 stars, 0.2 stars and 0.3 stars for House 1 in Hobart, Brisbane and Melbourne respectively.

For House 1, the decrease from 90% to 70% in the acceptability limits reduces cooling loads by 13.3% in Darwin, 34.6% in Alice Springs and 36.2% in Mildura (see Fig. 7). For House 2, it reduces cooling load by 2.3% in Darwin, 39.1% in Alice Springs and 26.6% in Mildura. For both houses in these three cities the decrease from 90% to 80% in the acceptability limits has greater impact on cooling load than that from 80% to 70%.

3.3. Simulation results for House 3(lightweight building) under current climate in hot climates

In warm tropical climates, lightweight buildings may achieve better

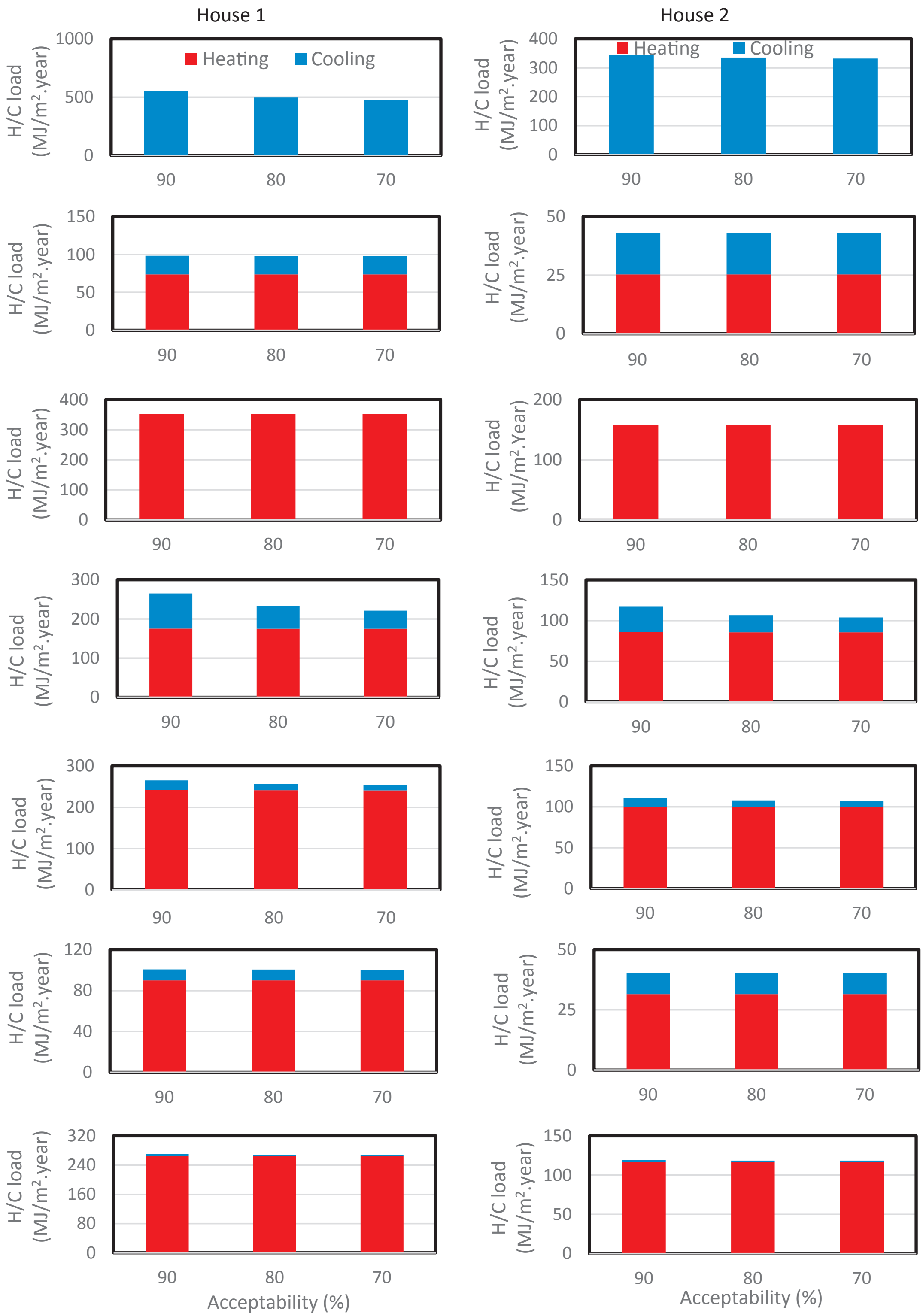

Fig. 6. Sensitivity of space H/C loads to indoor thermal acceptability limits under current climate for House 1 with 3 stars and House 2 with 6 stars in the seven cities: Darwin, Brisbane, Hobart, Alice Springs, Mildura, Sydney and Melbourne (from top to bottom).

thermal comfort after sunset by removing unwanted heat quickly. In tropical and sub-tropical regions in Australia, there are high-set lightweight houses, which are raised off the ground to facilitate cross ventilation to cool down the buildings quickly at night. House 3 is a lightweight house with timber/uPVC frame single glazed clear glass windows and medium size gaps of the windows and doors. Its floor is raised 2.32 m off the ground with under floor space totally open to the surroundings. The impact of relaxing the thermal comfort criteria on its energy performance under current climate in the four regions with hot to very hot summer (Darwin- tropical, Brisbane -subtropical, Alice Springs and Mildura both having hot dry summer) is shown in Fig. 8. Except in Darwin, the energy performance is poor (below 1 star even with 70% of the acceptability limits) and significant energy is required for space heating in the other three regions. With the decrease from

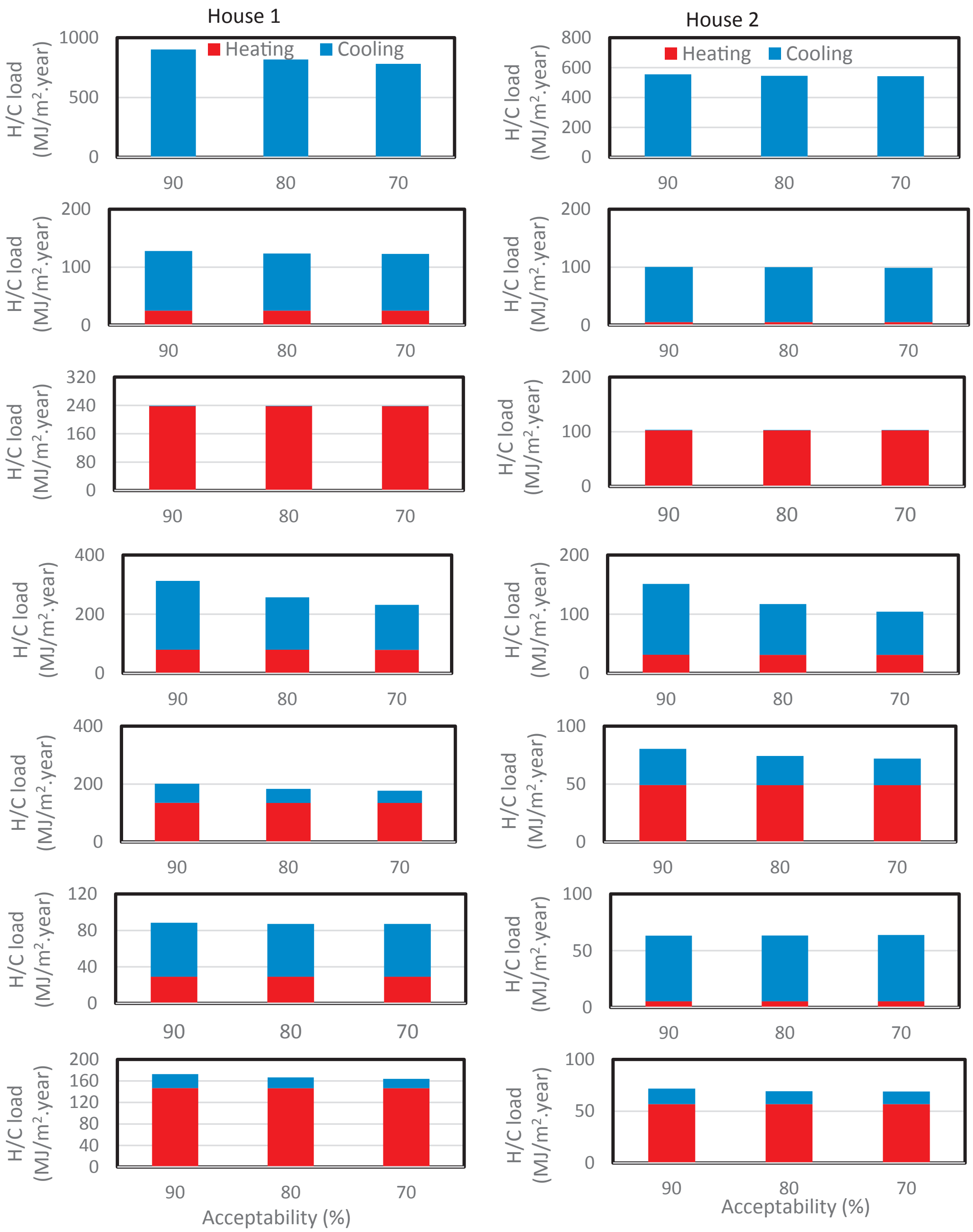

Fig. 7. Sensitivity of space H/C loads to indoor thermal acceptability limits under future climate for House 1 and House 2 in the seven cities: Darwin, Brisbane, Hobart, Alice Springs, Mildura, Sydney and Melbourne (from top to bottom).

Table 4
Impact of global warming of 2 °C on energy star rating of Houses 1 and 2 in the seven cities.

City	House 1 Acceptability (%)			House 2 Acceptability (%)		
	90	80	70	90	80	70
Darwin	0	0.7	0.9	3	3.1	3.2
Alice Springs	2.6	3.1	3.4	4.9	5.9	6.3
Mildura	3.8	4.1	4.3	7	7.2	7.3
Brisbane	2.2	2.3	2.4	2.9	2.9	2.9
Sydney	3.3	3.3	3.3	4.2	4.2	4.2
Melbourne	4.4	4.6	4.7	7.4	7.4	7.4
Hobart	4.3	4.4	4.4	7.2	7.2	7.2

90% to 70% in the acceptability limits, the space cooling loads are reduced by 45.5% in Darwin, 53.7% in Brisbane, 25.7% in Alice Springs and 24.7% in Mildura. With the decrease of the acceptability limits, the energy rating is increased by 3.6 stars (from 3.4 stars to 7 stars) in Darwin, 0.2 star in Brisbane, 0.3 star in Alice Springs and 0.5 star (from 0 to 0.5 star) in Mildura. In terms of the cooling load and energy rating, the decrease from 90% to 80% in the acceptability limits has greater impact than that from 80% to 70%.

Ceiling insulation and sealing cracks of windows and doors are relatively easy and economic measures to improve residential building energy efficiency. Fig. 9 shows the calculated energy requirement in the four regions when House 3 is improved by installing R3 insulation to the ceiling and weather stripping the cracks of the windows and doors. With this improvement under 90% of the acceptability limits

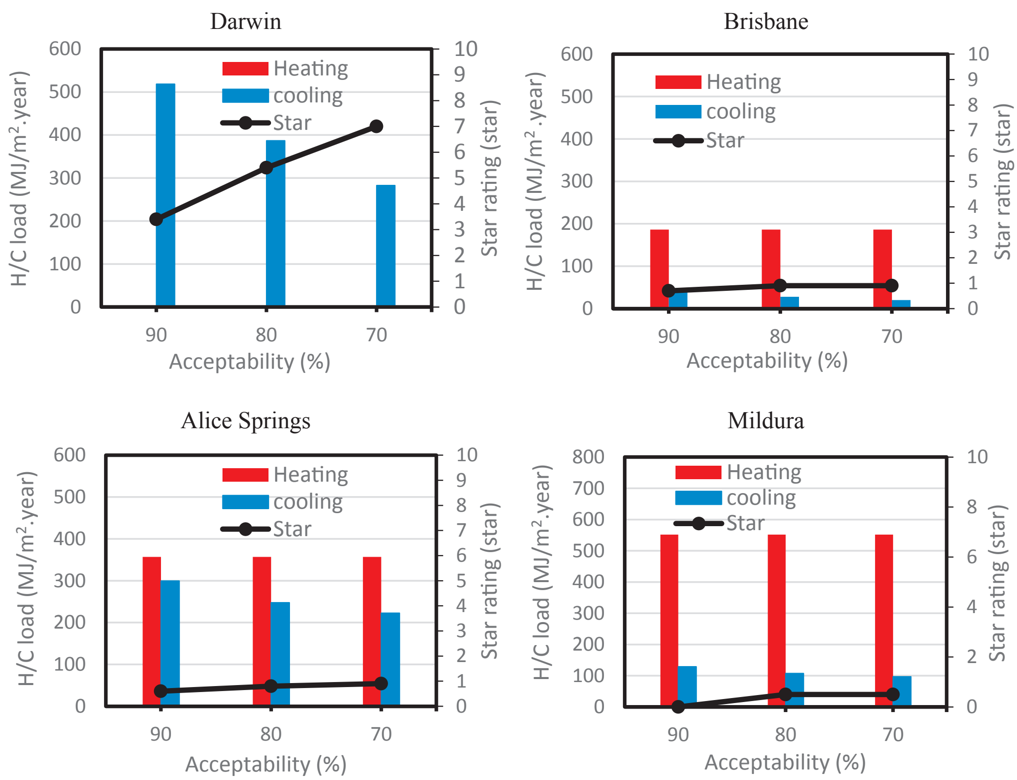

Fig. 8. Sensitivity of space H/C loads and star rating to indoor thermal acceptability limits under current climate for House 3 in the four regions with hot to very hot summer.

(implemented in the current version of AccuRate), 31% of the cooling load is reduced in Darwin, 46.5% in Brisbane, 42.3% in Alice Springs and 41.3% in Mildura (refer to Figs. 8 and 9). The space heating loads are also reduced significantly in Brisbane, Alice Springs and Mildura. The energy rating is increased by 2.5 stars (from 3.4 to 5.9 stars) in Darwin, 1.6 stars in Brisbane, 1.5 stars in Alice Springs and 1.7 stars (from 0 to 1.7 stars) in Mildura. With the decrease from 90% to 70% in the acceptability limits, the energy rating is increased further by 2.5 stars (from 5.9 to 8.4 stars) in Darwin, 0.3 star in Brisbane, 0.4 star in Alice Springs and 0.1 star in Mildura.

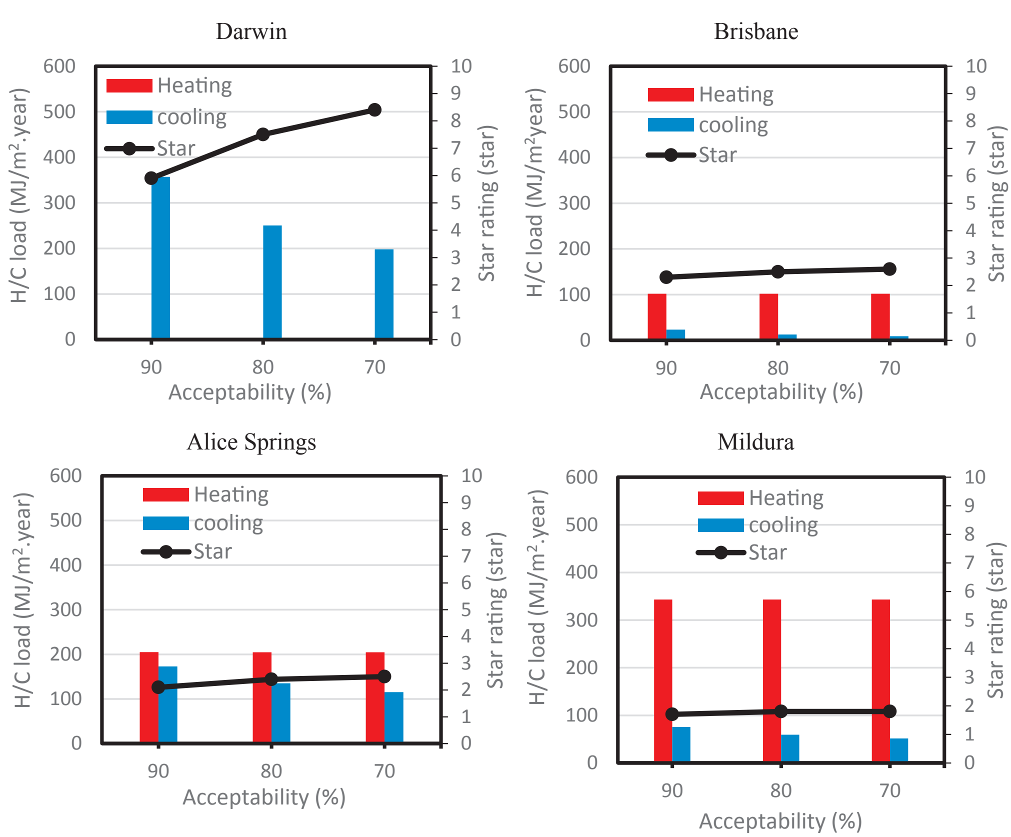

Fig. 9. Sensitivity of space H/C loads and star rating to indoor thermal acceptability limits under current climate for House 3 improved with R3 ceiling insulation and weather stripped windows and doors in the four regions.

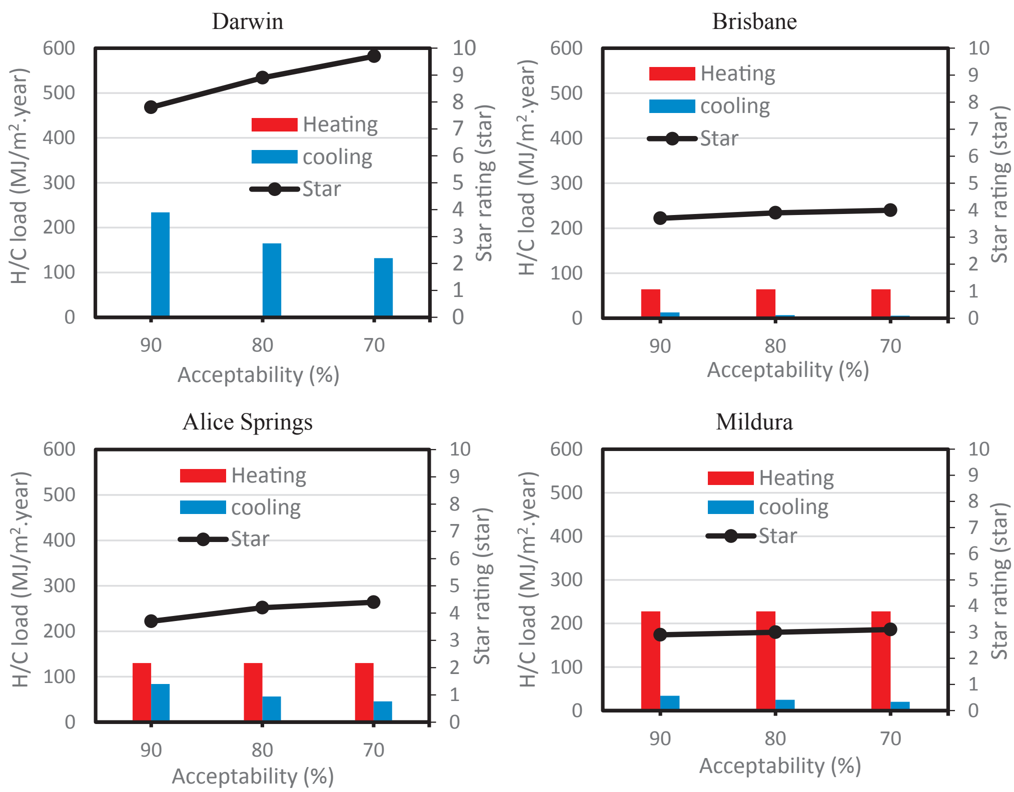

Fig. 10. Sensitivity of space H/C loads and star rating to indoor thermal acceptability limits under current climate for House 3 further significantly improved in the four regions.

To evaluate potential housing design with natural ventilation only, the performance of House 3 can be further significantly improved by insulating the ceiling up to R6 and the external wall with R3, and replacing the single glazed windows with high performance windows (Timber/uPVC frame double grazed with 10 mm Argon gap). The results are represented in Fig. 10. With 70% acceptability limits, House 3 can achieve an energy rating of 9.7 stars in Darwin and the cooling load in Brisbane can be reduced to 5.7 MJ/m^2.annum. This means air-conditioning used for cooling in the tropical and sub-tropical regions can be minimized with properly designed lightweight houses. With the decrease from 90% to 70% in the acceptability, the energy rating for the further improved House 3 is increased by 1.9 stars (from 7.8 to 9.7 stars) in Darwin, 0.3 star in Brisbane, 0.7 star in Alice Springs, and 0.2 star in Mildura. In comparison with House 1 and 2, House 3 appears to achieve the largest energy efficiency increase in Darwin by decreasing the acceptability from 90% to 70%.

3.4. Simulation results for House 3(lightweight building) under future climate in hot climates

With the global warming of 2 °C, the impact of relaxing thermal comfort criteria on energy performance of House 3 in the four regions (Darwin, Brisbane, Alice Springs and Mildura) is shown in Fig. 11. Except for Mildura, the assumed global warming makes the building energy performance worse (see Figs. 8 and 11). It reduces performance by 3.4 stars in Darwin, 0.7 star in Brisbane, 0.6 star in Alice Springs. However, it increases by 0.8 star in Mildura due to significant reduction in the heating load. With the acceptability of 90% (current setting in AccuRate), the global warming increases the cooling loads by 72.1% in Darwin, 266.1% in Brisbane, 86.2% in Alice Springs, and 87.2% in Mildura (see Figs. 8 and 11). With the decrease from 90% to 70% in the acceptability limits, the cooling loads are reduced by 22.8% in Darwin, 40.9% in Brisbane, 20.0% in Alice Springs and 23.2% in Mildura. With the decrease in the acceptability limits, the energy rating is increased by 1.6 stars in Darwin, 1.2 stars in Brisbane, 0.7 star in Alice Springs and 0.3 star in Mildura. In terms of cooling load and energy rating, the decrease from 90% to 80% in the acceptability limits has greater impact than that from 80% to 70%.

To evaluate potential house design under the future climates with natural ventilation only, House 3 was significantly improved by adding insulation of R6 to the ceiling and R3 to the external wall and replacing the windows with high performance windows (Timber/uPVC frame double grazed with 10 mm Argon gap). As shown in Fig. 12, the cooling loads are reduced more than half and energy star rating increased by more than 50% in all the four cities in comparison with those in Fig. 11. It can also be seen that even with the acceptability of 70%, the energy star ratings in the four cities are all blow 6 stars. It means that under the global warming of 2 °C it is very difficult to achieve thermal comfort with natural ventilation only for House 3 in these four climates.

4. Discussions and conclusions

To reduce energy consumption and carbon emissions in buildings, it is important to minimize unnecessary air conditioning. At the same time, potential energy efficiency technologies for building air conditioning systems should consider future climates so that efficiencies can still be achieved under changing conditions. For building design and operation, three acceptability classes of indoor temperature range are specified in the ISO, European and ASHRAE standards. In general, more energy is required to maintain a narrower indoor temperature range compared to a broader range. However, few studies have been reported to have a critical analysis on the range (i.e., acceptability limits) on residential building energy performance for space air conditioning for different house constructions in different local climates. In this study, three houses with different thermal performance and constructions (House1- combination, House 2- heavyweight, and House 3- lightweight) are evaluated in the seven major Australian NCC climate zones under the current and future climates. The following main conclusions can be drawn:

- In the seven NCC climate regions under both the current and future climates, for space cooling load, the acceptability limits have greater

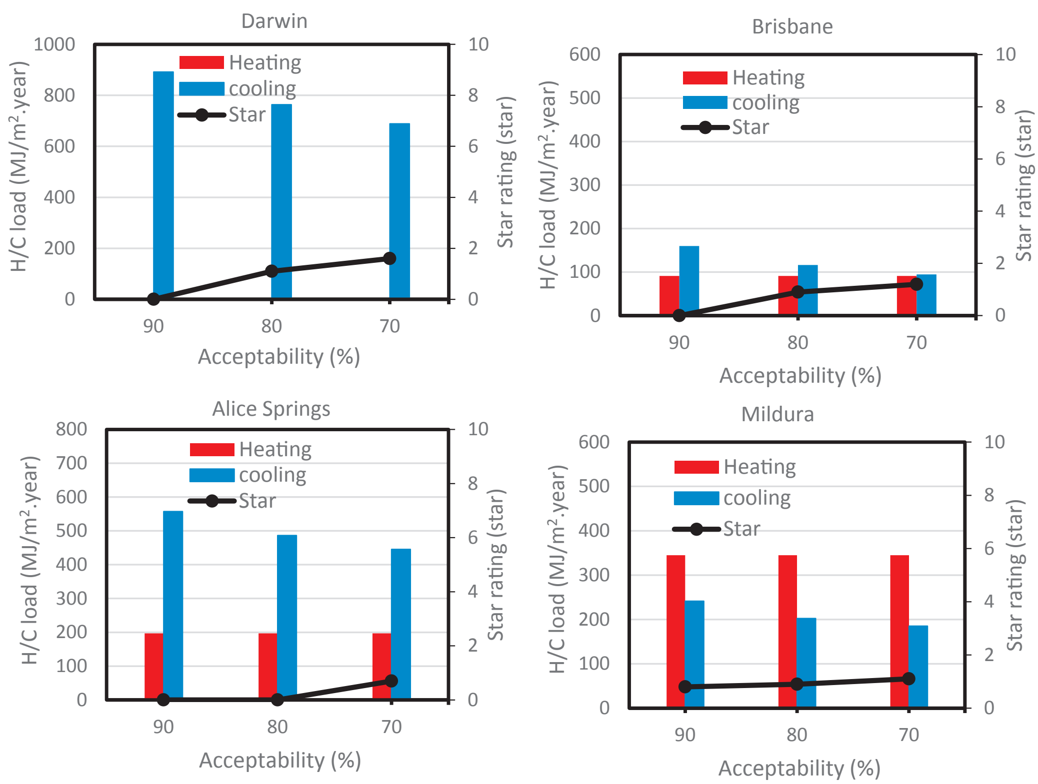

Fig. 11. Sensitivity of space H/C loads and star rating to indoor thermal acceptability limits under future climate for House 3 in the four regions with hot to very hot summer.

impact on the medium weight colourbond slab-on-ground (House 1) than on the heavy double brick cavity houses (House 2);

- The decrease from 90% to 80% in the acceptability limits has a greater reduction in space cooling load than the decrease from 80% to 70%;
- In terms of space cooling energy requirements and house energy rating for Houses 1 and 2, the impact of reducing the acceptability limit (from 90% to 70%) is minor or can be ignored under current climate in heating/cooling balanced regions (Brisbane and Sydney) and heating dominated regions (Melbourne and Hobart). The most impacted region is in tropical regions such as Darwin, and it increases 1 star for House 1 and 0.2 star for House 2 due to the

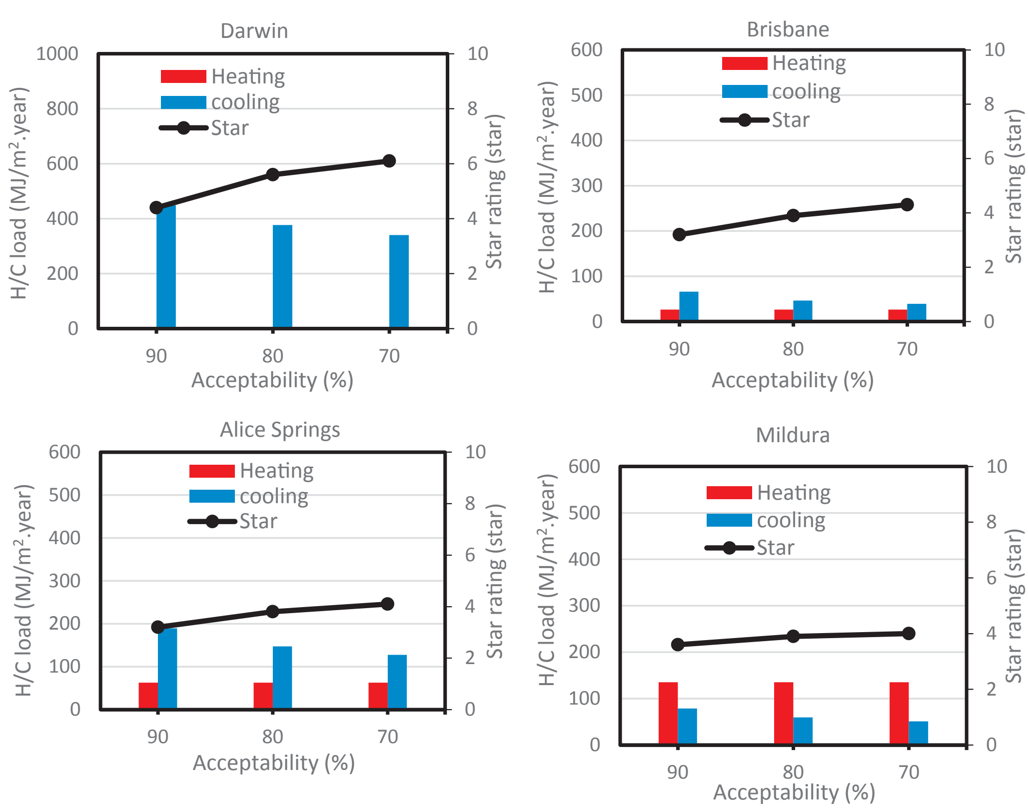

Fig. 12. Sensitivity of space H/C loads and star rating to indoor thermal acceptability limits under future climate for House 3 further significantly improved in the four regions.

decrease from 90% to 70% in the acceptability limits;

- With the global warming temperature of 2 °C, the impact of the decrease in the acceptability limits will still be minor for Brisbane, Sydney and Hobart. In Melbourne it will increase cooling loads of Houses 1 and 2 by around 33% and 18% respectively. In terms of cooling load and energy rating for both houses, the most impacted warm tropical region is Alice Springs, where relaxing acceptability reduces cooling loads of Houses 1 and 2 by around 35% and 39%, and increases energy star ratings of Houses 1 and 2 by 0.8 star and 1.4 stars, respectively;
- For high-set lightweight houses (House 3), which are common in warm tropical regions, under current climate the decrease from 90% to 70% in the acceptability limits increases 3.6 stars in Darwin, 0.5 star in Mildura, 0.3 star in Alice Springs and 0.2 star in Brisbane;
- It is shown that for properly designed high-set lightweight houses, the energy used for space cooling can be minimized in tropical regions (9.7 stars achieved in Darwin) and subtropical regions (reduced to 5.7 MJ/m^2.annum in Brisbane) using 70% acceptability limits. This can encourage to reduce space cooling loads in tropical and subtropical regions through proper lightweight construction house design and operation;
- Compared to the current climate, global warming will reduce the impact of relaxing the acceptability limits on cooling load reduction and energy star rating of the lightweight houses.

The impact of the acceptability limits on space cooling loads is dependent upon the building design, operation, and local climate. Although the case studies were all made for Australian climates, the above general findings should be applicable in similar climates and construction types worldwide.

As mentioned in ASHRAE Standard 55-2013 [3], the 80% acceptability limits are for typical applications and 90% acceptability limits are applied when a high standard of thermal comfort is desired. The 90% acceptability limits are implemented in the current version of AccuRate for house energy star rating in Australia with a high standard of thermal comfort. The 90% acceptability limits for houses may be too strict for residential houses considering that house occupants normally have more options to adjust their thermal comfort through opening windows, turning on fans, changing clothes, etc. in comparison with occupants in office buildings.

This study quantified the impact of thermal comfort acceptability limits on residential building air conditioning energy consumption for different house constructions in different climate regions in Australia. Further study is undergoing to investigate what extent the thermal comfort acceptability limits are acceptable for residential buildings in reality in various Australia climates. With both this study and the investigation of the real acceptability limits, proper thermal comfort acceptability limits can be proposed and implemented in design tools and energy rating schemes for residential buildings in Australia. This will facilitate and encourage more energy efficient house designs in Australian, especially for tropical and sub-tropical regions.

References

[1] Rupp R, Vásquez N, Lamberts R. A review of human thermal comfort in the built environment. Energy Build 2015;105:178–205.
[2] Hoyt T, Lee K, Zhang H, Arens E, Webster T. Energy savings from extended air temperature set points and reductions in room air mixing. Paper presented at the International Conference on Environmental Ergonomics, Boston, August 2–7, 2009.
[3] ASHRAE. ANSI/ASHRAE Standard 55-2013:Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigeration and Ai-Conditioning Engineers Inc., Atlanta; 2013.
[4] Fanger P. Thermal comfort: analysis and applications in environmental engineering. Copenhagen: Danish Technical Press; 1970.
[5] Nicol F, Humphreys M, Roaf S. Adaptive thermal comfort: principles and practice. Abingdon: Routledge; 2012.
[6] de Dear R, Brager G. Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 1998;104:145–67.
[7] Humphreys M. Thermal comfort requirements, climate and energy. In: Sayigh AAM, editor. The second world renewable energy congress. Pergamon; 1992.
[8] Humphreys M, Nicol J. Understanding the adaptive approach to thermal comfort, field studies of thermal comfort and adaptation. ASHRAE Tech Data Bull 1998;14:1–14.
[9] Humphreys M, Nicol J. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy Build 2002;34:667–84.
[10] de Dear R, Brager G. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy Build 2002;34:549–61.
[11] Nicol J, Humphreys M. Thermal comfort as part of a self-regulating system. Build Res Pract 1973;1:174–9.
[12] Nicol F, Humphreys M. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 2002;34:563–72.
[13] Nicol F, Humphreys M. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Build Environ 2010;45:11–7.
[14] Auliciems A. Towards a psycho-physiological model. Int J Biometeorol 1981;25:109–22.
[15] de Dear R, Brager G, Cooper D. Developing an adaptive model of thermal comfort and preference. Final Report ASHRAE RP-884; 1997.
[16] Humphreys M, Rijal H, Nicol J. Updating the adaptive relation between climate and comfort indoors: new insights and an extended database. Build Environ 2013;63:40–55.
[17] Hoof J, Hensen J. Quantifying relevance of adaptive thermal comfort models in moderate climate zones. Build Environ 2007;42:156–70.
[18] Taleghani M, Tenpierik M, Kurvers S, Dobellsteen A. A review into thermal comfort in buildings. Renew Sustain Energy Rev 2013;26:201–15.
[19] Mishra A, Ramgopal M. Field studies on human thermal comfort – an review. Build Environ 2013;64:94–106.
[20] Yang L, Yan H, Lam J. Thermal comfort and building energy consumption implications – a review. Appl Energy 2014;115:164–73.
[21] Kwong Q, Adam N, Sahari B. Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: a review. Energy Build 2014;68:547–57.
[22] Han J, Zhang G, Zhang Q, Zhang J, Liu J, Tian L, et al. Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China. Build Environ 2007;42:4043–50.
[23] Chen H, Zhu Y. Energy saving and thermal comfort problems of residential buildings which adopt concentrated HVAC system. J Harbin Inst Technol (New Series) 2007;14:176–8.
[24] Yoshino H, Yoshino Y, Zhang Q, Mochida A, Li N, Li Z, et al. Indoor thermal environment and energy saving for urban residential buildings in China. Energy Build 2006;38:1308–19.
[25] Hong S, Gilbertson J, Oreszczyn T, Green G, Ridley I. A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. Build Environ 2009;44:1228–36.
[26] Romero R, Bojórquez G, Corral M, Gallegos R. Energy and the occupant's thermal perception of low-income dwellings in hot-dry climate: Mexicali, México. Renew Energy 2013;49:267–70.
[27] Derbez M, Berthineau B, Cochet V, Pignon C, Ribéron J, Wyart G, et al. A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses. Build Environ 2006;82:288–99.
[28] Tweed C, Dixon D, Hinton E, Bickerstaff K. Thermal comfort practices in the home and their impact on energy consumption. Arch Eng Des Manage 2014;10:1–24.
[29] Moon J, Han S. Thermostat strategies impact on energy consumption in residential buildings. Energy Build 2013;43:338–46.
[30] Karunakaran R, Iniyan S, Goic R. Energy efficient fuzzy based combined variable refrigerant volume and variable air volume air conditioning for buildings. Appl Energy 2010;87:1158–75.
[31] Tzivanidis C, Antonopoulos K, Gioti F. Numerical simulation of cooling energy consumption in connection with thermostat operation mode and comfort requirements for Athens buildings. Appl Energy 2011;88:2871–84.
[32] Peeters L, de Dear R, Hensen J, D'haeseleer W. Thermal comfort in residential buildings: comfort values and scales for building energy simulation. Appl Energy 2009;86:772–80.
[33] Singh M, Mahapatra S, Atreya S. Adaptive thermal model for different climatic zones of North-East India. Appl Energy 2011;88:2420–8.
[34] Roussac A, Steinfeld J, de Dear R. A preliminary evaluation of two strategies for raising indoor air temperature set points in office buildings. Arch Sci Rev 2011;54:148–56.
[35] Al-Sanea S, Zedan M. Optimized monthly-fixed thermostat-setting scheme for maximum energy-savings and thermal comfort in air-conditioned spaces. Appl Energy 2008;85:326–46.
[36] Van der Linder A, Boerstra A, Raue A, Kurvers S, de Dear R. Adaptive temperature limits: a new guideline in the Netherlands: a new approach for the assessment of building performance with respect to thermal indoor climate. Energy Build 2006;38:8–17.
[37] Ogbonna A, Harris D. Thermal comfort in sub-Saharan Africa: field study report in Jos-Nigeria. Appl Energy 2008;85:1–11.
[38] Nicol J, Humphreys M. New standards for comfort and energy use in buildings. Build Res Inform 2009;37:68–73.
[39] Roaf S, Nicol F, Humphreys M, Tuohy P, Boerstra A. Twentieth century standards for thermal comfort: promoting high energy buildings. Arch Sci Rev 2010;53:65–77.
[40] Yao R, Liu J, Li B. Occupants' adaptive response and perception of thermal environment in naturally conditioned university classrooms. Appl Energy 2010;87:1015–22.
[41] Indraganti M. Thermal comfort in naturally ventilated apartments in summer:

findings from a field study in Hyderabad, India. Appl Energy 2010;87:866–83.
[42] Panao M, Camelo S, Goncalves H. Assessment of the Portuguese building thermal code: newly revised requirements for cooling energy needs used to prevent the overheating of buildings in the summer. Energy 2011;36:3262–71.
[43] Cândido C, Lamberts R, de Dear R, Bittencourt L, de Vecchi R. Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. Build Res Inform 2011;39:145–53.
[44] Yun G, Kong H, Kim J. The effect of seasons and prevailing environments on adaptive comfort temperatures in open plan office. Indoor Built Environ 2012;21:41–7.
[45] Liang H, Lin T, Hwang R. Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. Appl Energy 2012;94:355–63.
[46] Li B, Yao R, Wang Q, Pan Y. An introduction to the Chinese Evaluation Standard for the indoor thermal environment. Energy Build 2014;82:27–36.
[47] International Standard Organization. ISO 7730-2005: Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria; 2005.
[48] European Standard. EN 15251-2007: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings—Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics; 2007.
[49] Attia S, Carlucci S. Impact of different comfort models on zero energy residential buildings in hot climate. Energy Build 2015;102:117–28.
[50] Kim J, de Dear R, Parkinson T, Candido C, Cooper P, Ma Z, Saman W. Field study of air conditioning and thermal comfort in residential buildings. In: Proceeding of 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, UK, April 7-10, 2016.
[51] Shiel J, Aynsley R, Moghtaderi B, Page A. The importance of air movement in warm temperatures: a novel SET* house case study. Arch Sci Rev 2017;60:225–38.
[52] Holmes M, Hacker J. Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. Energy Build 2007;36:802–14.
[53] Tuohy P, Roaf S, Nicol F, Humphreys M, Boerstra A. Twenty first century standards for thermal comfort: fostering low carbon building design and operation. Arch Sci Rev 2010;53:78–86.
[54] Wan K, Li D, Liu D, Lam J. Future trends of building heating and cooling loads and energy consumption in different climates. Build Environ 2011;46:223–34.
[55] Nicol J. Temperature and adaptive comfort in heated, cooled and free-running dwellings. Build Res Inform 2017. http://dx.doi.org/10.1080/09613218.2017.1283922.
[56] Baharun A, Ooi K, Chen D. Thermal comfort and occupant behaviours in AccuRate – a software assessing the thermal performance of residential buildings in Australia. In: Proceeding of EERB-BEPH, Guilin, China, May 29–31, 2009.
[57] Delsante A. Is the new generation building energy rating software up to the task? – A review of AccuRate." Paper presented at ABCB Conference 'Building Australia's Future 2005', Surfers Paradise, September 11–15, 2005.
[58] Ren Z, Paevere P, Grozev G, Egan S, Anticev J. Assessment of end-use electricity and peak demand Townsville's housing stock. Energy Policy 2013;61:888–93.
[59] Walsh P, Delsante A. Calculation of the thermal behaviour of multi-zone buildings. Energy Build 1983;5:231–42.
[60] Ren Z, Chen D. Enhanced air flow modelling for AccuRate – a nationwide house energy rating tool in Australia. Build Environ 2010;45:1276–86.
[61] NatHERS National Administer. Nationwide House Energy Rating Scheme (NatHERS) – Software Accreditation Protocol; 2012. Available from < http://www.nathers.gov.au > [accessed 09/09/2017].
[62] Delsante A. A validation of the AccuRate simulation engine using BESTEST. Report for Australia greenhouse Office, CMIT-2004-152; 2004.
[63] ABCB (Australian Building Codes Board). Protocol for House Energy Rating Software; 2006. Available from < http://www.abcb.gov.au > [accessed 09/09/2017].
[64] Aynsley R, Szokolay S. Options for Assessment of Thermal Comfort/Discomfort for Aggregation into NatHERS Star Ratings. James Cook University Report; 1998.
[65] Wang X, Chen D, Ren Z. Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Build Environ 2010;4:1663–82.
[66] Gordon H, O'Farrell S, Collier M, Dix M, Rotstayn L, Kowalczyk E, Hirst T, Watterson I. The CSIRO MK3.5 climate model. The Centre for Australian Weather and Climate Research Technical Report NO.021;2010. Available from < http://www.cawcr.gov.au > [accessed on 15/06/2017].
[67] Belcher S, Hacker J, Powell D. Constructing design weather data for future climates. Build Serv Eng Res Technol 2010;26:49–61.
[68] Reardon C, Downton P. Your Home – Australia's guide environmentally sustainable homes: Passive Design; 2013. Available from < http://www.yourhome.gov.au > [accessed on 09/06/2017].
[69] Murray G, Dale H. Composition of Australia's housing. HIA Economics Research Note; 2015. Available from < https://hia.com.au > [accessed on 09/06/2017].
[70] Ren Z, Paevere P, McNamara C. A local-community-level, physically-based model of end-use energy consumption by Australian housing stock. Energy Policy 2012;49:586–96.
[71] Arens E, Humphreys M, de Dear R, Zhang H. Are 'Class A' temperature requirements realistic or desirable? Build Environ 2010;45:4–10.